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Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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13. ABSTRACT

In large experimental thermonuclear installations with adiabatic magnetic compression of the plasma, there is required in a number of cases the creation of magnetic fields of trapezoidal shape with the duration of the peak exceeding by 1 to 2 orders of magnitude the duration of the pulse front. For satisfaction of these requirements, several variants of pulse systems were developed: 1) A two stage system using a capacitor battery and a direct current generator with a special device for separating high voltage and low voltage circuits; 2) A two stage circuit with a capacitor battery and an inductive accumulator, charged by a capacitor battery of comparatively low voltage; 3) A two stage system with the use of a capacitor battery and an artificial line. An analysis of the processes in the developed system is considered. The principal data and parameters of the pulse systems are presented. [AP1123067]

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Circuit						
Parameter						
Magnetoactive Plasma						
Magnetic Field						
Adiabatic Compression						
Capacitor						
Battery						

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

F. M.

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

SYSTEMS FOR THE GENERATION OF HIGH-POWER PROGRAMMED PULSES IN APPARATUS WITH ADIABATIC MAGNETIC COMPRESSION OF PLASMA

A. M. Stolov, Doctor of Technical Sciences; S. M. Spevakova, Candidate of Technical Sciences; B. A. Larionov, Engineer; and D. Ye. Zavarin, Engineer

The authors discuss methods for shaping high-power pulses in an inductive load. An analysis is made of the processes occurring in the systems considered, with methods presented for the selection of circuit elements. Pertinent data are cited for the pulse circuits developed.

In large experimental thermonuclear apparatus with adiabatic magnetic compression, special requirements are sometimes demanded of the character of the variation of the magnetic fields in time. In equipment of this type the field rise time is limited by the conditions affecting the reduction of plasma losses in the trap, and normally should not exceed 10^{-2}-10^{-3} s, while in some cases it should be even less. Along with this rather stringent requirement for systems with a high energy margin, the pulse-power systems for apparatus with adiabatic magnetic compression must ensure, following the rise of the field, that this field will be maintained at its assigned value for a period of time more than 1-2 orders of magnitude greater than the duration of the leading edge of the

pulse. This factor has necessitated the development of special programmed supply systems of extremely high power for a variety of experimental apparatus.

In these situations pulse-shaping methods using tube circuits and nonlinear elements are inapplicable because of power deficits. On the other hand, the direct use, for these purposes, of artificial lines is inadvisable for systems with heavy energy reserve because of the low utilization factor of the line's energy margin when working with an active-inductive load.

It will be recalled that the required field pulse form in apparatus with adiabatic plasma compression can be achieved for systems in which it is technically expedient to design the excitation winding with a time constant greater than the required pulse duration. In this case, the rapid build-up of the field may be accomplished through the use of the energy of a precharged capacitor battery, with the field held constant by shorting out the oscillatory circuit formed by the capacitor battery and the load at maximum current. This type of circuit calls for the use of switching devices rated for a relatively long current flow with a comparatively low firing voltage as compared to the voltage applied to the switching element.

More complex is pulse-shape programming in systems which require substantial power to raise the field and which possess a time constant which is small with respect to the duration of the pulse. This kind of problem is encountered, for example, in the design of stellarator traps and probkotrons* with a comparatively low firing voltage as compared to the voltage applied to the switching element.

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*[Translator's Note: The term "probkotron" is given here exactly as it appears in the Russian text. The precise meaning is unclear. The root "probka" may variously indicate a plug, a plug-type fuse, a kind of end-stopper, or a plug gage.]

The analysis conducted, along with a comparison of different methods of pulse-shaping, has indicated that in many cases, for the parameter ratios indicated, the best approach is through the use of two-stage systems consisting of two power supplies operating against a common load. One of these sources is to generate the necessary power to raise the field and must have an energy assurance-factor store approximately corresponding to the energy of the magnetic field of the load; the second source is designed to cover the active losses for the flat portion of the pulse.

A capacitor battery provides a convenient energy source for building up the field within a broad range of energy margins, while the selection of the second power-supply unit depends on the power of the active losses and the pulse duration. Possible alternatives for this second source might be a direct-current generator, an inductive storage circuit (tank), or an artificial line. The applied features of each of these three options were investigated.

A two-stage system consisting of a capacitor battery and a dc generator is capable of shaping pulses of the form shown in Fig. 1. These pulses are formed by the periodic (within time intervals τ) discharge of the capacitor battery across a rectifier switching device to the load in such a way that the battery discharge current is directed in opposition to the generator current. The implementation of this circuit entails certain technical difficulties occasioned by the need to keep the circuits separate and the substantial difference in the voltage levels of the battery and generator (the latter designed to cover the active losses), as well as by the need to restrict to a permissible value the maximum rate of change of the generator current derivative during the pulse.

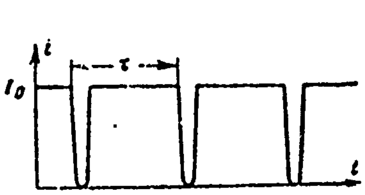

Fig. 1. Generated pulses.

A special pulse-shaping circuit was devised (Fig. 2) whose use virtually eliminates the variable component in the dc generator

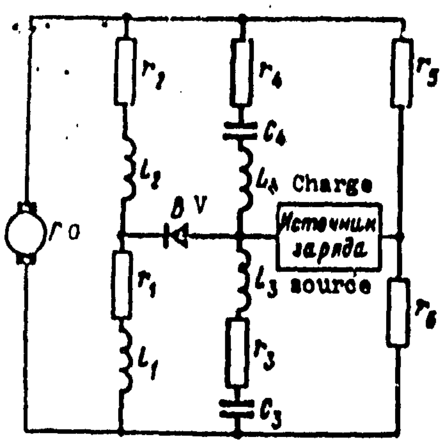

Fig. 2. DC generator pulse-shaping circuit: G - generator; L_1, r_1 - load parameters; L_2. r_2 - compensating reactor parameters; L_3, L_4 - protective reactor; C_3, C_4 - capacitor batteries of primary and compensating circuits.

circuit, while at the same time ensuring an acceptably reliable separation of circuits [1].

This separation of the dc circuit and the capacitor battery discharge circuit is brougnt about through the introduction of a supplementary compensating circuit, the parameter ratio of which L_2, r_2, C_3, r_3, L_3 is so selected that the discharge frequency and attenuation equal the frequency and attenuation of the fundamental circuit. The selection of the compensating circuit parameters is basically dictated by economic considerations (minimum total cost of the inductance and capacitance of the circuit). Since the possibility of capacitor breakdown must be kept in mind when working with large capacitor batteries (resulting in the possible flow of sizable pulsed currents across the dc source), the circuit encorporates a double-coil balanced reactor-limiter L_3, L_4. The latter must be designed with reasonably good magnetic coupling between the coils lest it limit the discharge current under normal operating conditions.

Precharged capacitor batteries C_3 and C_4 discharge simultaneously across switching valve V. In the discharge phase the voltages on L_1 and L_2 are in opposition. In operator form the current flowing across the dc generator during the discharge period of capacitors C_3 and C_4 can be represented by the following expression:

$$I_0 = \frac{\left(N + pM\frac{S}{z_1}\right)\left(z_2 + \frac{z_2 z_3}{z_1} - pM\right) - \left(z_3 + z_4 - pM\frac{z_3}{z_1}\right)\left[K - S\left(1 + \frac{z_3}{z_1}\right)\right]}{\left[z_2 - pM\left(1 + \frac{z_2}{z_1}\right)\right]\left(z_3 + \frac{z_2 z_3}{z_1} - pM\right) - \left(z_3 + z_4 - pM\frac{z_3}{z_1}\right)\left[z_2 + z_3\left(1 + \frac{z_2}{z_1}\right)\right]}, \quad (1)$$

where

$$z_1 = r_1 + pL_1, \quad z_2 = r_2 + pL_2,$$
$$z_3 = r_3 + pL_3 + \frac{1}{pC_3}, \quad z_4 = r_4 + pL_4 + \frac{1}{pC_4},$$
$$N = pL_2 i_{20} - U_{40}, \quad K = pL_1 i_{10} - U_{30},$$
$$S = pL_1 i_{10} - pL_2 i_{20} + E_0,$$

M is the mutual induction coefficient between the branches of the protective reactor; E_0 is the generator voltage; i_{10}, i_{20} are the initial values of the cirrent in load L_1 and in reactor L_2; U_{30}, U_{40} are the initial values of the voltage of capacitor batteries C_3 and C_4.

In order that during the discharge of capacitor batteries C_3 and C_4 no variable component be present in the generator circuit and the current equal the constant value I_0, the circuit parameter ratios must be determined by the equations:

$$r_1 r_4 - r_2 r_3 + \frac{L_1}{C_4} - \frac{L_2}{C_3} = 0, \quad (2)$$

$$r_1 L_4 + r_4 L_1 - r_2 L_3 - r_3 L_2 = M(r_2 - r_1), \quad (3)$$

$$L_1 L_4 - L_2 L_3 = M(L_2 L_1), \quad (4)$$

$$\frac{r_1}{C_4} - \frac{r_2}{C_3} = 0. \quad (5)$$

On the basis of the circuit arrangement described above, a feed system was developed for the magnetic trap of an experimental apparatus representing a probkotron with a stabilizing field and adiabatic plasma compression. The basic parameters of this feed system are cited in the following table.

Table

Parameters	Primary field excitation system	Stabilizing field excitation system
Capacitor battery energy store, J....................	$1.7 \cdot 10^6$	10^6
Maximum voltage, kV...........	10	5
Maximum current, A...........	$16 \cdot 10^3$	$15.7 \cdot 10^3$
Maintenance duration of assigned field value, s.....	0.3-0.5	0.3-0.5
Field rise time, s............	$15 \cdot 10^{-3}$	$15 \cdot 10^{-3}$
Maximum dc generator power, kW.	$12 \cdot 10^3$	$11.8 \cdot 10^3$

This circuit can be recommended for systems in which the power of the active losses is relatively restricted (e.g., 10^3-10^4 kW), but in which a considerable pulse duration (fractions of a second and more) occasions the need to spend large energy reserves on the losses.

A two-stage shaping circuit for heavy pulsed currents was devised and tested, in which an inductive storage device (tank) was employed as the second stage [2]. In this arrangement (Fig. 3) a fast build-up of the current in winding L_1 is ensured by high-voltage low-induction capacitor battery C_1, with the pulse plateau formed by connecting in series with the load, at the proper time, the storage inductance L_0 in which there has been pre-excited a current from the relatively low-voltage capacitor battery C_2. This arrangement provides for the shaping of heavy pulsed currents by means of the inductive circuit without the use of disconnecting switching apparatus. Current switching is handled by controlled spark gaps which cut in the circuit elements according to the appropriate time sequence. The duration of the pulse plateau depends on the sum time constant of the load and tank. The nature of the process is markedly affected by the presence of stray (spurious) inductances in the system. Spurious parameters lead to the occurrence in the load current of superimposed variable

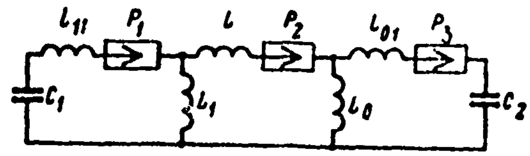

Fig. 3. Pulse-shaping circuit with inductive storage device (tank): P_1, P_2, P_3 - spark gaps; L_1 - load; L_0 - inductive storage device; L_{11}, L, L_{01} - stray inductances; C_1, C_2 - capacitor batteries.

components of comparatively high frequency. In large measure, the amplitude of these components is determined by the firing potential of spark gap P_2 and also by the $L_{01} + L/L_1$ inductance ratio.

The expression for the load current following the connection of spark gap P_2 appears as follows:

$$\begin{aligned} i = {} & i_0'(0) - \left[i_0(0) - \frac{L_1}{L_1 + L_{01} + L} i_1(0)\right] \cos\omega_0 t + \\ & + \left(1 + \frac{L_{01}}{L_0}\right) U_0 C_0 \omega_0 \sin\omega_0 t + \left(\frac{L_{01} + L}{L_1 + L_{01} + L}\right) i_1(0) \cos\omega_1 t - \\ & - \left(1 + \frac{L_{11}}{L}\right) U_1 C_1 \omega_1 \sin\omega_1 t, \end{aligned} \tag{6}$$

where $i_0(0)$, $i_1(0)$ are the currents of inductances L_0 and L_1, respectively, at the moment of engagement of spark gap P_2; U_0 and U_1 are the voltages to these inductances at the moment of engagement.

$$\omega_1 = \sqrt{\left[L_{11} + \frac{L_1(L + L_{01})}{L_1 + L_{01} + L}\right] C_1}, \tag{7}$$

$$\omega_0 = \sqrt{\left[L_{01} + \frac{L_0(L + L_1)}{L_0 + L + L_{01}}\right] C_0}. \tag{8}$$

By selecting the initial conditions so that

$$i_0 = \frac{L_1}{L_1 + L_0 + L} i_1,$$

the current expression will assume the form:

$$I = I_0(0)\left[1 + \frac{L_{01}+L}{L_1}\cos\omega_1 t - \left(1+\frac{L_{11}}{L_1}\right)\times \right.$$
$$\left.\times\frac{\omega_1 C_1 U_s}{I_0(0)}\sin\omega_1 t\right], \qquad (9)$$

where $U_s = U_0 - U_1$ is the firing voltage for spark gap P_2.

In accordance with this circuit arrangement, an apparatus was designed having the following parameters:

Maximum current value in coil, kA........	280
Current rise time to maximum value, s....	$16 \cdot 10^{-6}$
Current decay time to half the maximum value, s................................	$1.8 \cdot 10^{-3}$
Stored energy of battery C_1, kJ..........	160
Voltage of battery C_1, kV.................	50
Stored energy of battery C_2, kJ..........	500
Voltage of battery C_2, kV.................	5

The switching elements used included: P_1, P_2 - vacuum arrestors; P_3 - spark gaps.

Figure 4 shows oscillograms of the current in the load.

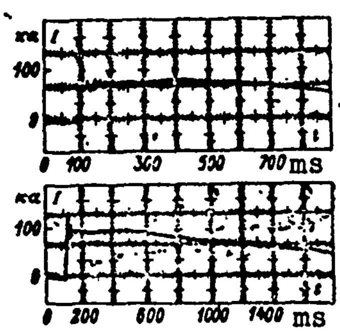

Fig. 4. Load current oscillograms.

This two-stage inductive tank circuit can be successfully used in high-power (about 10^5-10^7 kW) magnetic systems, but of the kind having realtively low energy storage corresponding to short pulses of about 10^{-3}-10^{-2} s duration. With this circuit, by making fairly stringent demands on the constancy of the current

in the working interval, it is possible to use only a negligible portion of the energy stored in the inductive tank and, thus, of the capacitor battery energy as well.

More advantageous in terms of power is a two-stage arrangement in which the second stage is an artificial line. Before considering the ratios in a two-stage circuit of this type, let us note that when an artificial line is directly employed for pulse-shaping with an active-inductive load, the utilization factor of the energy stored in the line is comparatively low and is characterized by the expression:

$$\frac{W_{эм}+W_R}{W_л} \approx \frac{1+2\frac{t_и}{T_{эм}}}{3\frac{t_и}{t_ф}}, \qquad (10)$$

where W is the electromagnetic energy of the load; W_R are the active energy losses in the load during the pulse; $W_л$ is the energy stored in the line; $t_и$ is the duration of the flat portion of the pulse; $t_ф$ is the rise time of the pulse; $T_{эм}$ is the load time constant.

A two-stage circuit using an artificial line [3] is shown in Fig. 5. The rapid build-up of the magnetic field in the load is achieved by the discharge of precharged capacitor battery C_0 when switching element K1 is cut into the circuit. After the load current has attained its maximum value i_0, the artificial line is connected to the load by means of switching element K2, its capacitors having been charged to voltage E_0. By properly matching the parameters of the line and the system voltages, the current can be kept constant in the load within the required time frame (Fig. 6).

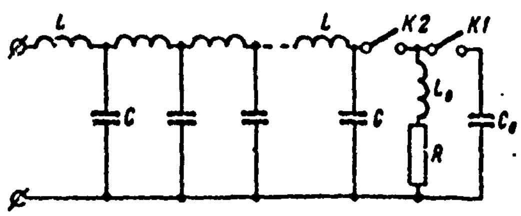

Fig. 5. Pulse-shaping circuit using artificial line: L_0, R - load parameters; C_0 - capacitor battery for initial field excitation; K_1, K_2 - switching elements.

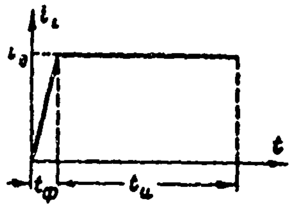

Fig. 6. Generated pulse.

The line-capacitor charge voltage E_0 must be so selected as to meet the condition

$$E_0 = U_0\left(1 + \frac{\rho}{R}\right), \qquad (11)$$

where $U_0 = i_0 R$ is the voltage of capacitor battery C_0 at the moment the line is connected; ρ is the characteristic impedance of the line; R is the load resistance.

It is possible to show that, disregarding the losses in the line, the load current can be represented in operator form by the following series [Translator's Note: in which the subscript letter "н" beneath the "i" indicateds "load"]:

$$\begin{aligned} i_н = i_0 [1 &+ e^{-2al}(1-\lambda) - \lambda e^{-4al}(1-\lambda) + \\ &+ \lambda^2(1-\lambda)e^{-6al} - \ldots -], \end{aligned} \qquad (12)$$

where

$$\lambda = \frac{p^2\rho C_0 L_0 + p\rho C_0 R + \rho - pL_0 - R}{p^2\rho C_0 L_0 + p\rho C_0 R + \rho + pL_0 + R} < 1,$$
$$a = p\sqrt{LC}.$$

L, C are parameters of the line elements; l is the length of the line.

Within a time interval equal to twice the transit time of the wave in the line, the current in the load is kept virtually constant, after which this constancy is lost, with the current representing the sum of the damped harmonic components.

To reduce the total energy stored in the line it is recommended that the parameters be chosen so that $\rho = R$. In this event, disregarding line losses, the utilization factor for the energy of capacitor battery C_0 and the capacitors of the line will be close to one.

Note that the use of these two-stage pulse-shaping systems with capacitor batteries as the first stage is recommended whenever the magnetic field energy does not exceed 10^7 J. Further increases in magnetic field energy will require the development of special high-power pulse sources designed according to other principles.

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